

# Quark-Gluon Plasma: The Stuff of the Early Universe

Paul Stankus

Oak Ridge Nat'l Lab

APS 09 April Meeting

## *Contents*

Expanding universe lightning review

Nuclear particles in the thermal early universe

Experimental evidence; how does it fit in?

# The original Hubble Diagram

“A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae”  
E. Hubble  
(1929)

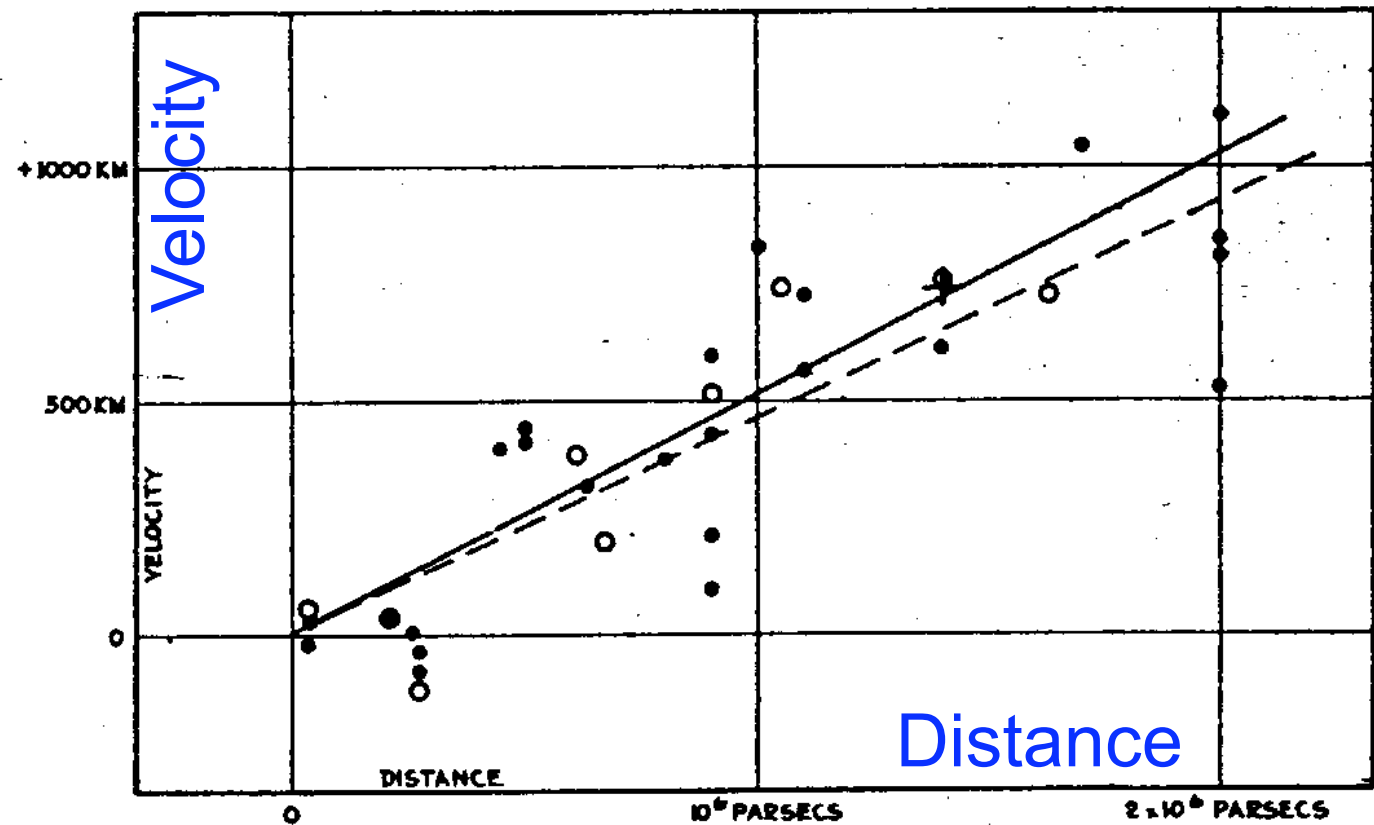


FIGURE 1



**Edwin Hubble**

American

Galaxies outside  
Milky Way



**Henrietta**

**Leavitt**

American

Distances via  
variable stars

As seen from our position:

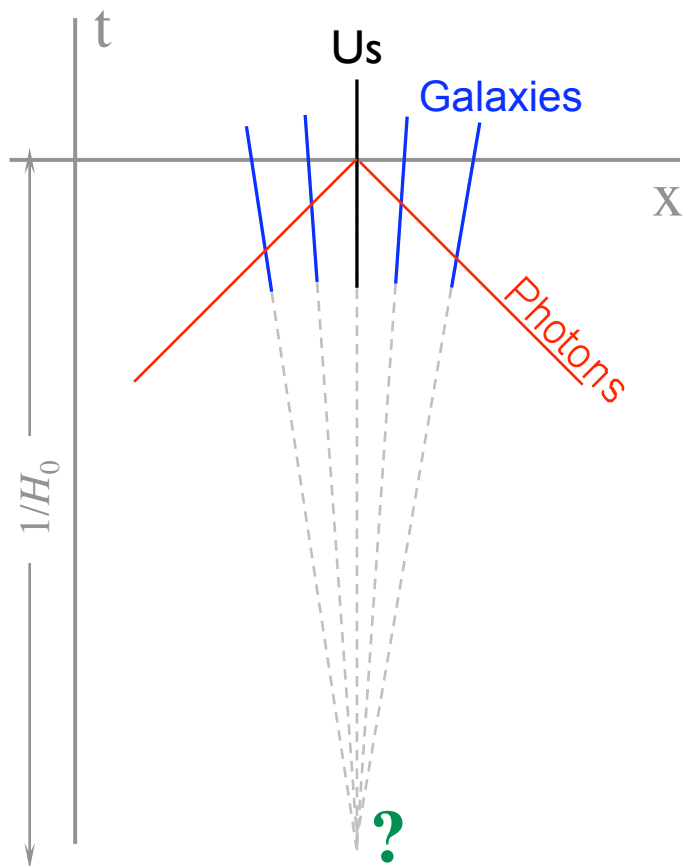
As seen from another position:



# Slightly Earlier

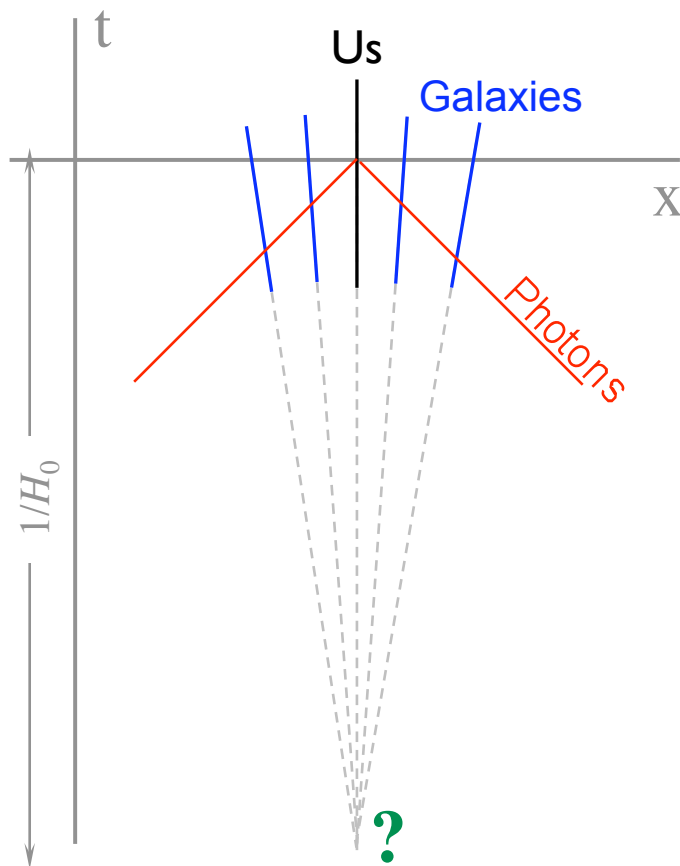


## Same pattern seen by all observers!



$$v_{\text{Recession}} = H_0 d$$

$1/H_0 \sim 10^{10} \text{ year} \sim \text{Age of the Universe?}$



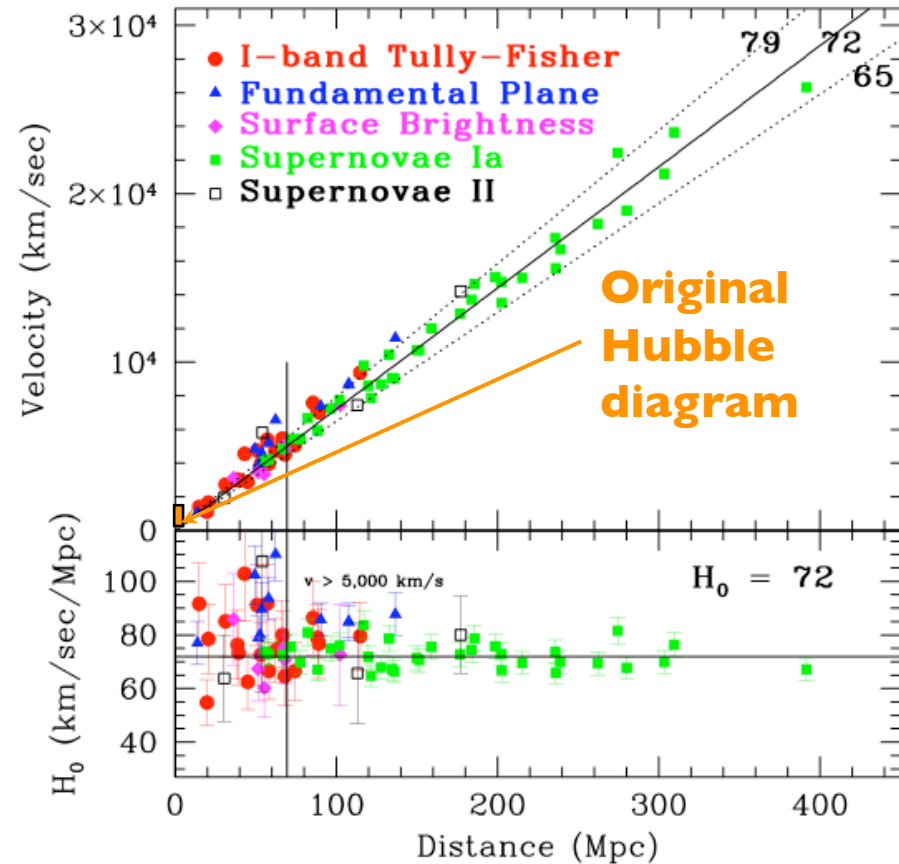
$$v_{\text{Recession}} = H_0 d$$

$1/H_0 \sim 10^{10}$  year  $\sim$  Age of the Universe?

Freedman, et al.  
Astrophys. J. **553**,  
47 (2001)

**W. Freedman**  
Canadian

Modern Hubble  
constant (2001)



1929:  $H_0 \sim 500$  km/sec/Mpc

2001:  $H_0 = 72 \pm 7$  km/sec/Mpc

# Minkowski Metric

$$d\tau^2 = -ds^2 = dt^2 - dx^2$$



**H. Minkowski**      German

“Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality” (1907)

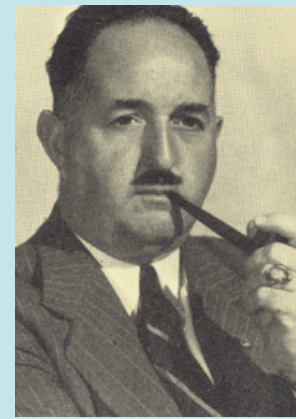
# Robertson-Walker Metric

$$d\tau^2 = -ds^2 = dt^2 - [a(t)]^2 d\chi^2$$

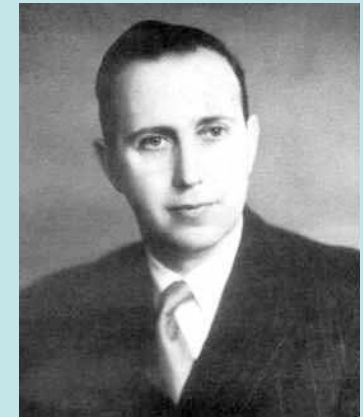
$a(t)$  dimensionless; set  $a(\text{now}) = 1$

$\chi$  has units of length

$a(t)\Delta\chi$  = physical separation at  $t$

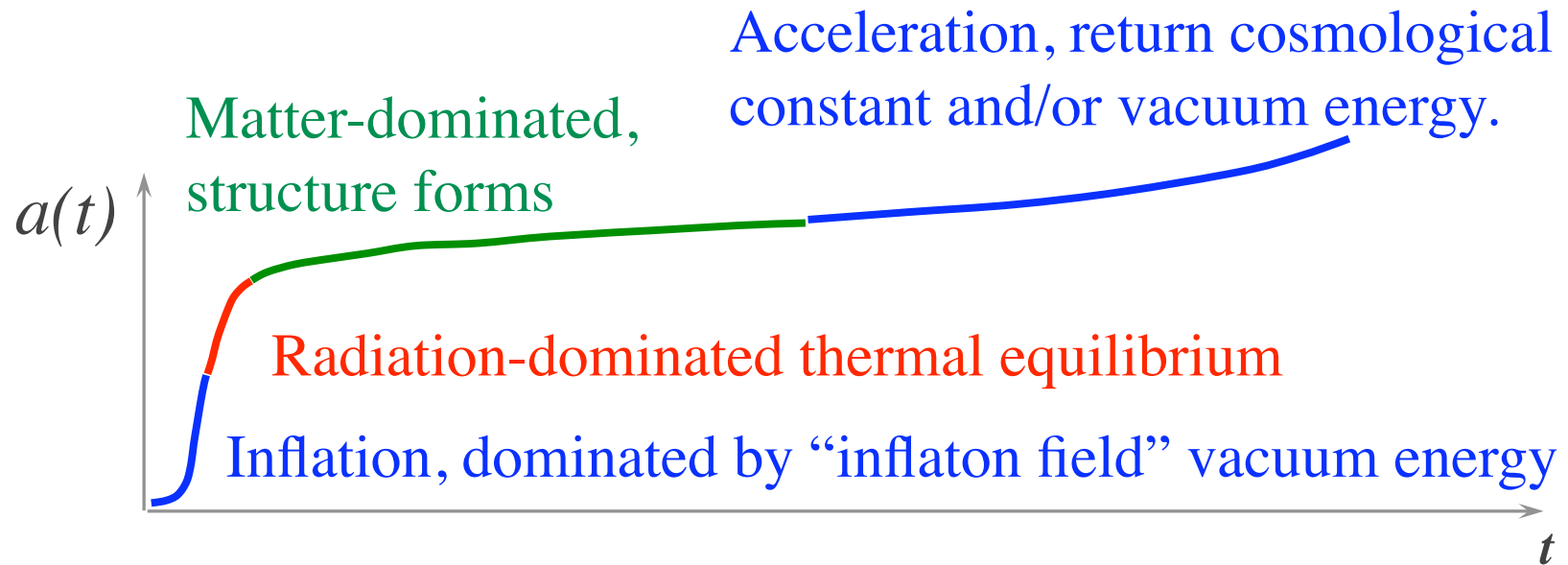


**H.P. Robertson**  
American

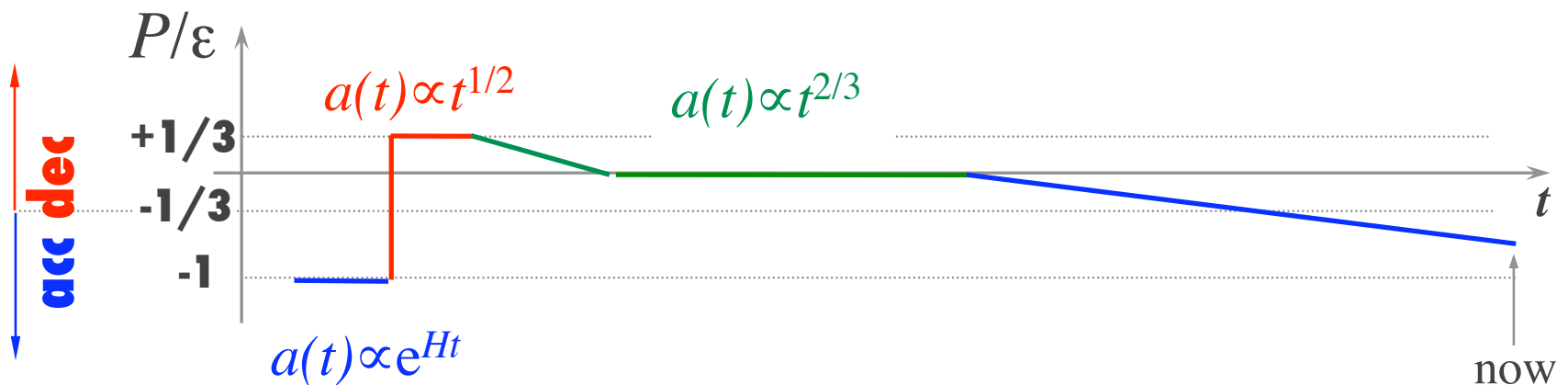


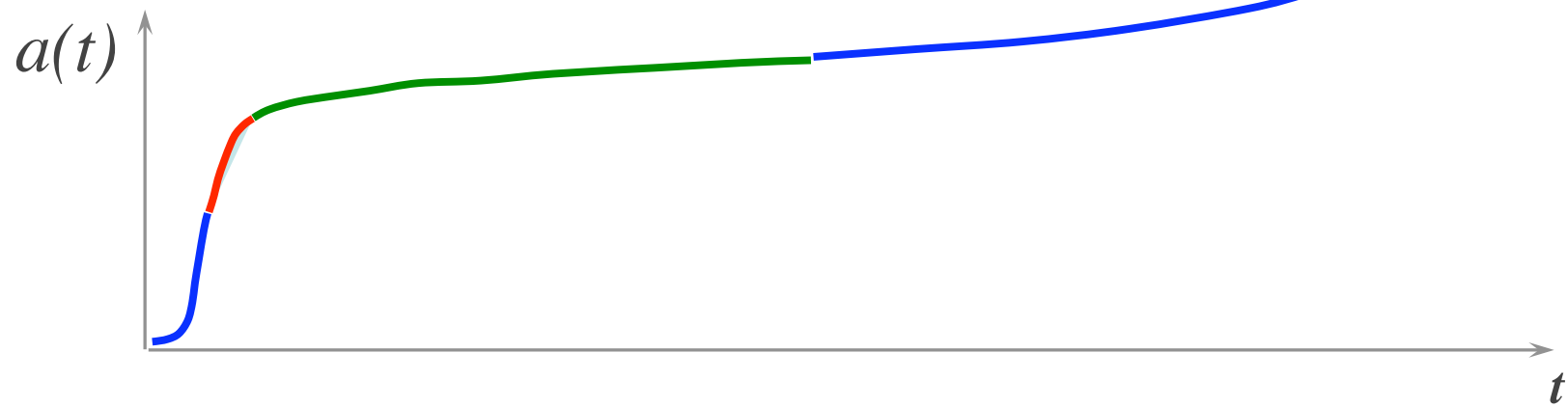
**A.G. Walker**  
British

Formalized most general form of isotropic and homogeneous universe in GR “Robertson-Walker metric” (1935-6)

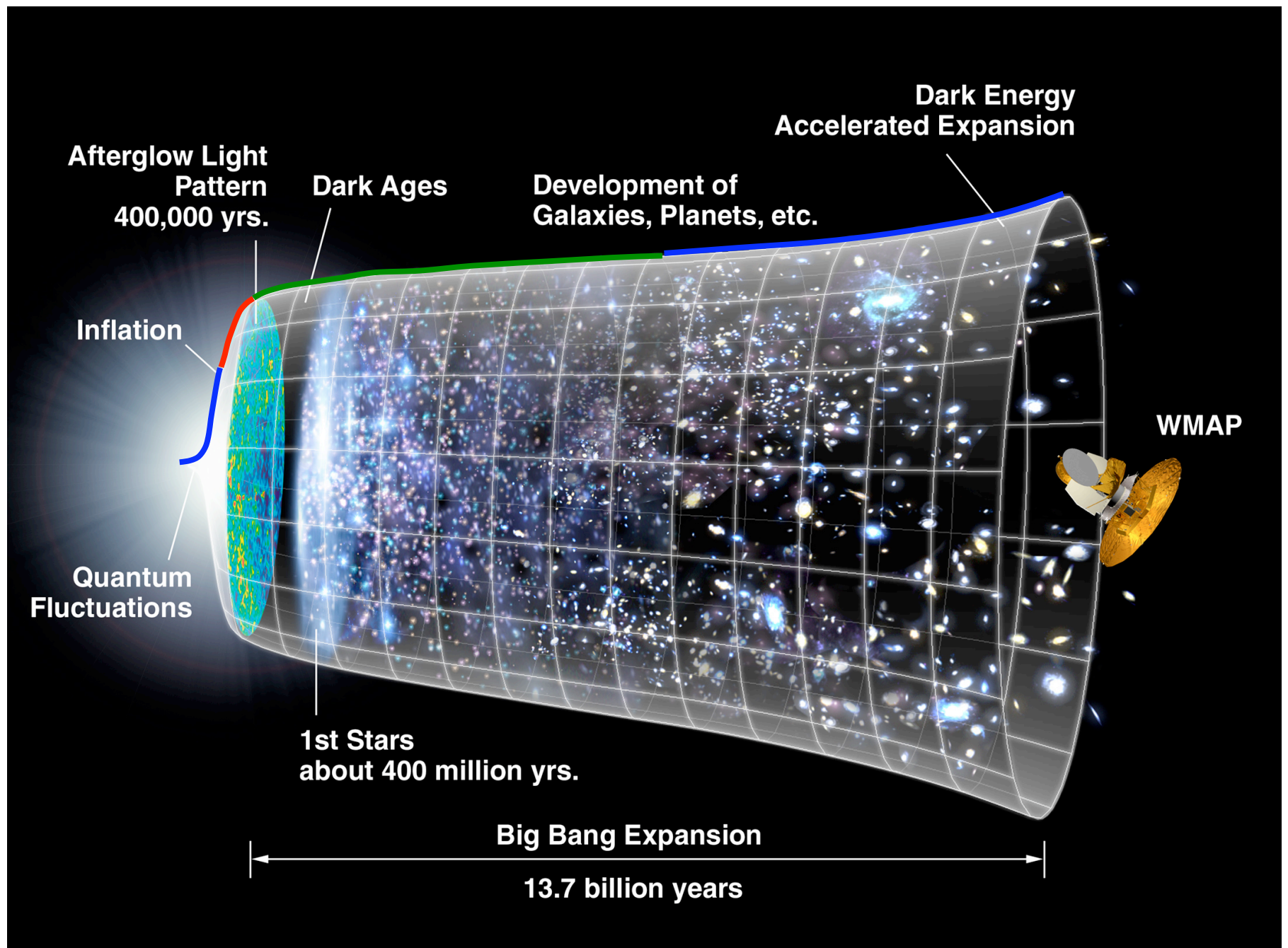


## The New Standard Cosmology in Four Easy Steps









# Basic Thermodynamics

$$dE = TdS - PdV$$

Hot

Hot

Hot

Sudden expansion, fluid fills empty space without loss of energy.

$$dE = 0 \quad PdV > 0 \quad \text{therefore} \quad dS > 0$$

Hot

Cool

Gradual expansion (equilibrium maintained), fluid loses energy through PdV work.

$$dE = -PdV \quad \text{therefore} \quad dS = 0$$

Isentropic  
Adiabatic

Golden Rule 1: Entropy per co-moving volume is conserved

Golden Rule 2: All entropy is in relativistic species

Expansion covers many decades in  $T$ , so typically either  $T \gg m$  (relativistic) or  $T \ll m$  (frozen out)

Golden Rule 3: All chemical potentials are negligible

Entropy  $S$  in co-moving volume  $(\Delta\chi)^3$  preserved

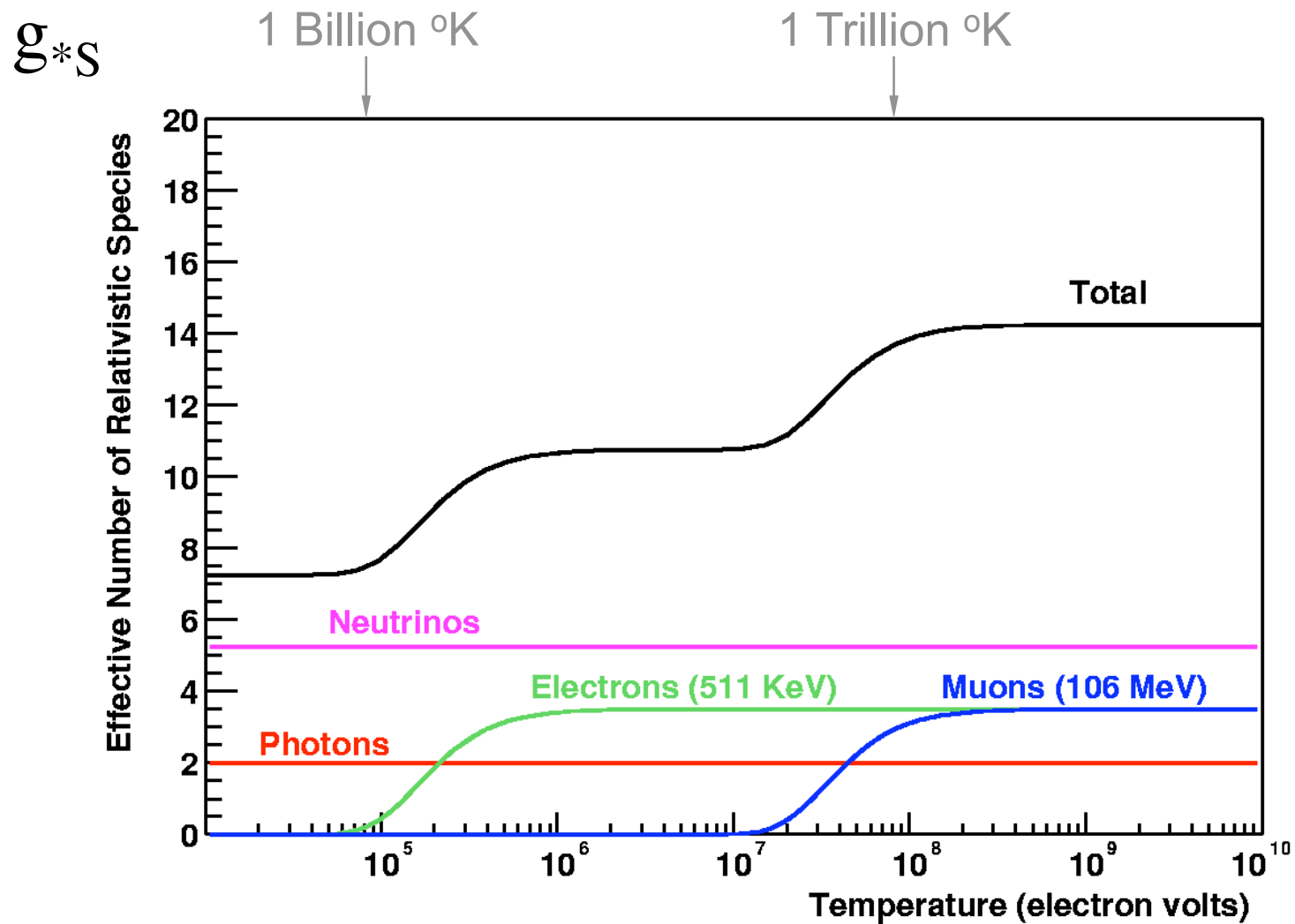
$$\text{Relativistic gas } \frac{S}{V} \equiv s = \sum_{\text{Particle Type}} s_{\text{Particle Type}} = \sum_{\text{Particle Type}} \left( \frac{2\pi^2}{45} \right) T^3 = \left( \frac{2\pi^2}{45} \right) g_{*S} T^3$$

$g_{*S} \equiv$  effective number of relativistic species

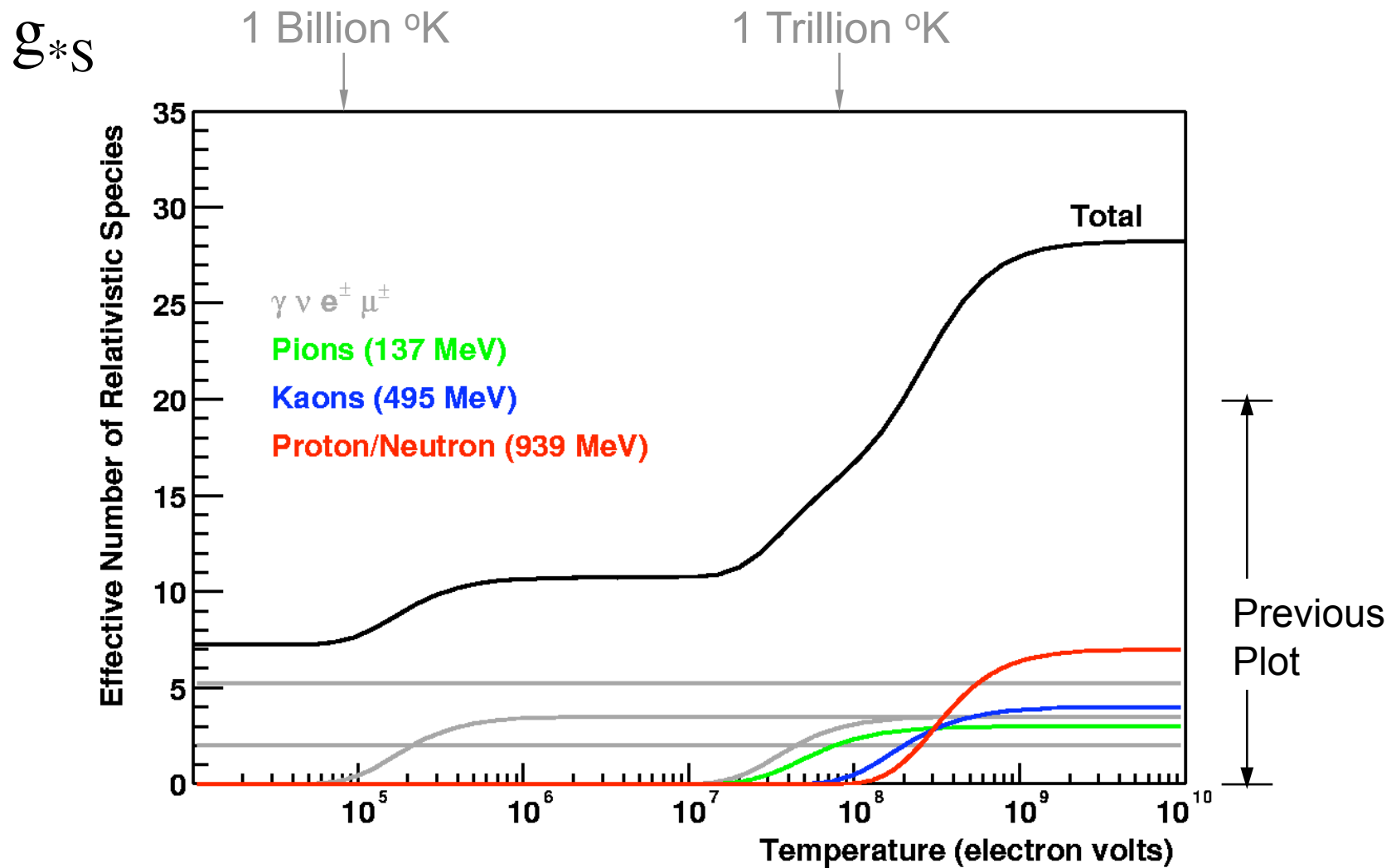
$$\text{Entropy density } \frac{S}{V} = \frac{S}{(\Delta\chi)^3} \frac{1}{a^3} = \frac{2\pi^2}{45} g_{*S} T^3$$

Golden Rule 4:

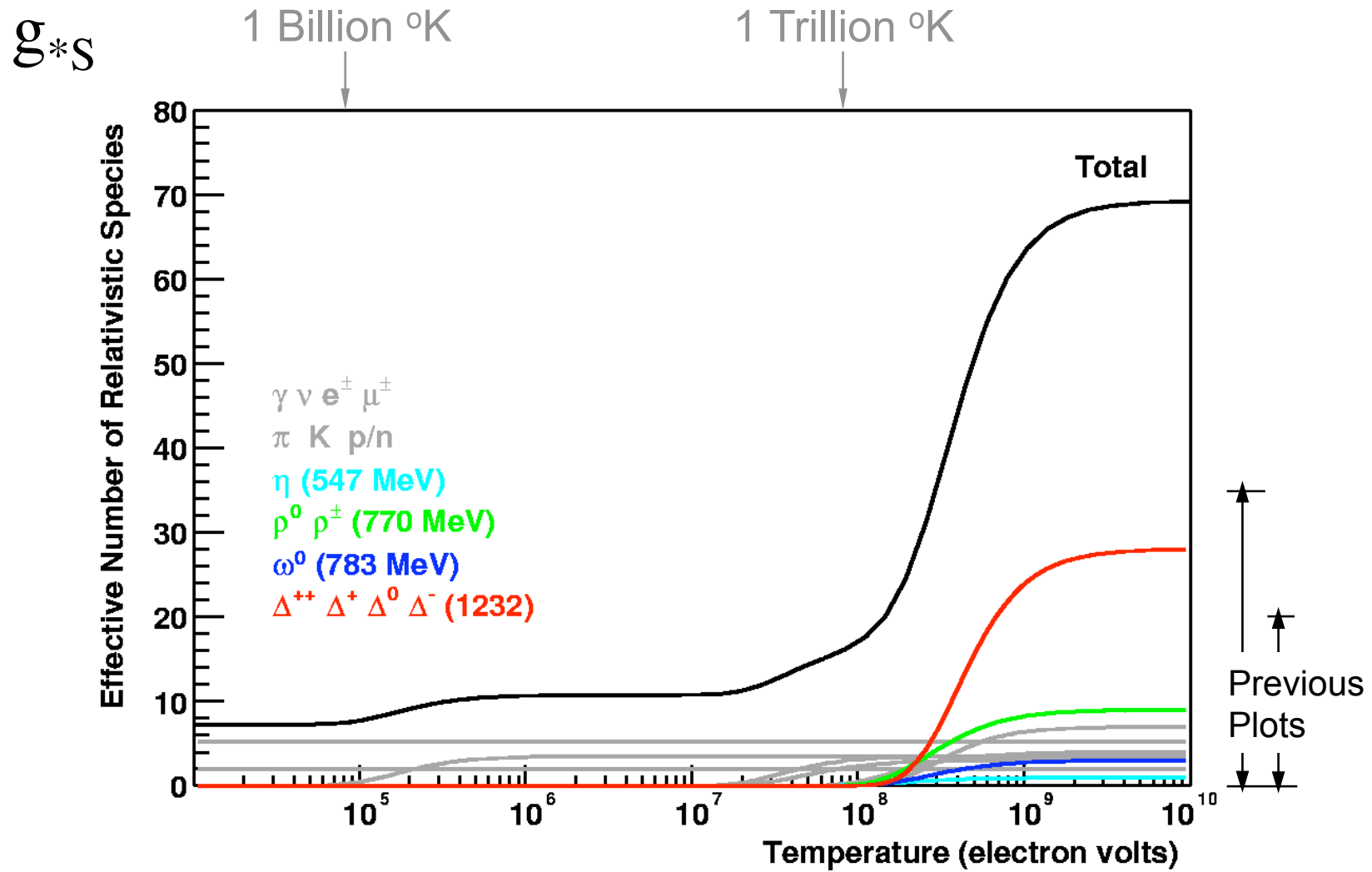
$$T \propto (g_{*S})^{-1/3} \frac{1}{a}$$



Start with light particles, no strong nuclear force



Now add *hadrons* = feel strong nuclear force



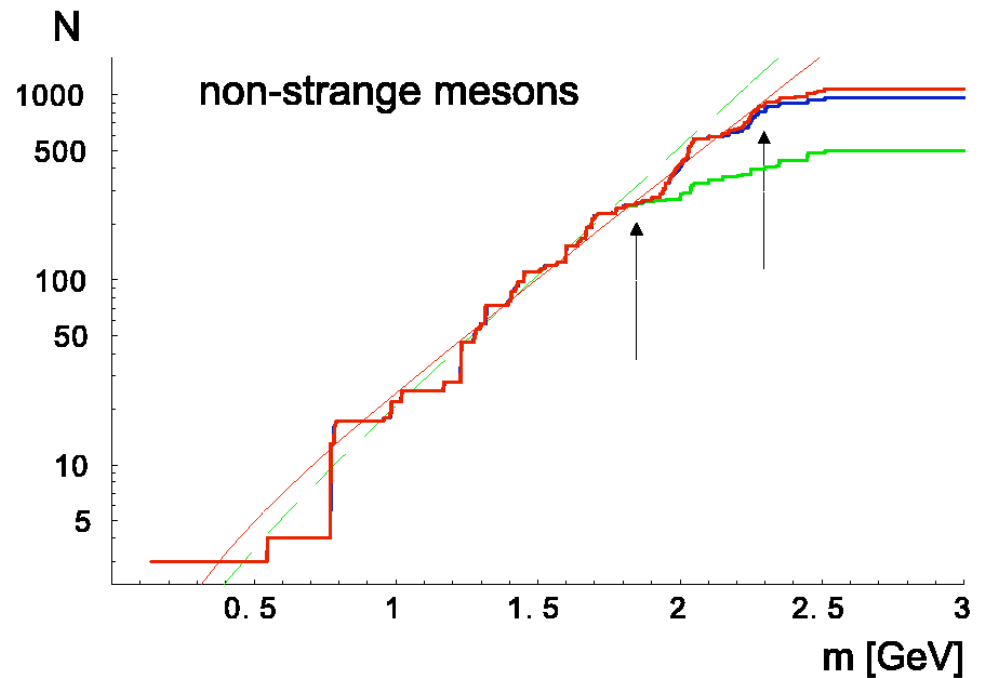
Keep adding more hadrons....

# How many hadrons?

Density of hadron mass states  $dN/dM$  increases exponentially with mass.

$$\frac{dN}{dM} \sim M^\alpha \exp\left(\frac{M}{T_H}\right)$$

$$T_H \sim 2 \times 10^{12} \text{ }^\circ\text{K} = 170 \text{ MeV}$$



Broniowski, et.al. 2004

Prior to the 1970's this was explained in several ways theoretically

**Statistical Bootstrap** Hadrons made of hadrons made of hadrons...

**Regge Trajectories** Stretchy rotators, first string theory

## Ordinary statistical mechanics:

$$E \sim \sum_{\text{states } i} E_i g_i \exp(-E_i/T) \sim \int E \frac{dN}{dE} \exp(-E/T) dE$$



## For thermal hadron gas (crudely set $E_i=M_i$ ):

$$E \sim \int_0^\infty M \frac{dN}{dM} \exp(-M/T) dM \quad \text{now add in } \frac{dN}{dM} \sim M^\alpha \exp(+M/T_H)$$
$$\sim \int_0^\infty M^\beta \exp\left(-M\left[\frac{1}{T} - \frac{1}{T_H}\right]\right) dM$$

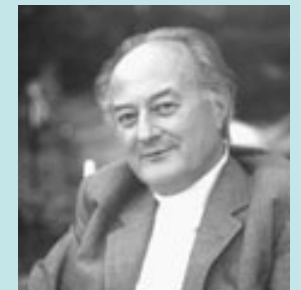
Energy **diverges** as  $T \rightarrow T_H$

*Ultimate Temperature in the Early Universe* K. Huang & S. Weinberg  
(Phys Rev Lett 25, 1970)

“...a veil, obscuring our view of the very beginning.” Steven Weinberg, *The First Three Minutes* (1977)

**Rolf Hagedorn**  
German

Hadron bootstrap  
model and limiting  
temperature (1965)





# QCD to the rescue!

Replace **Hadrons**  
(messy and  
numerous)

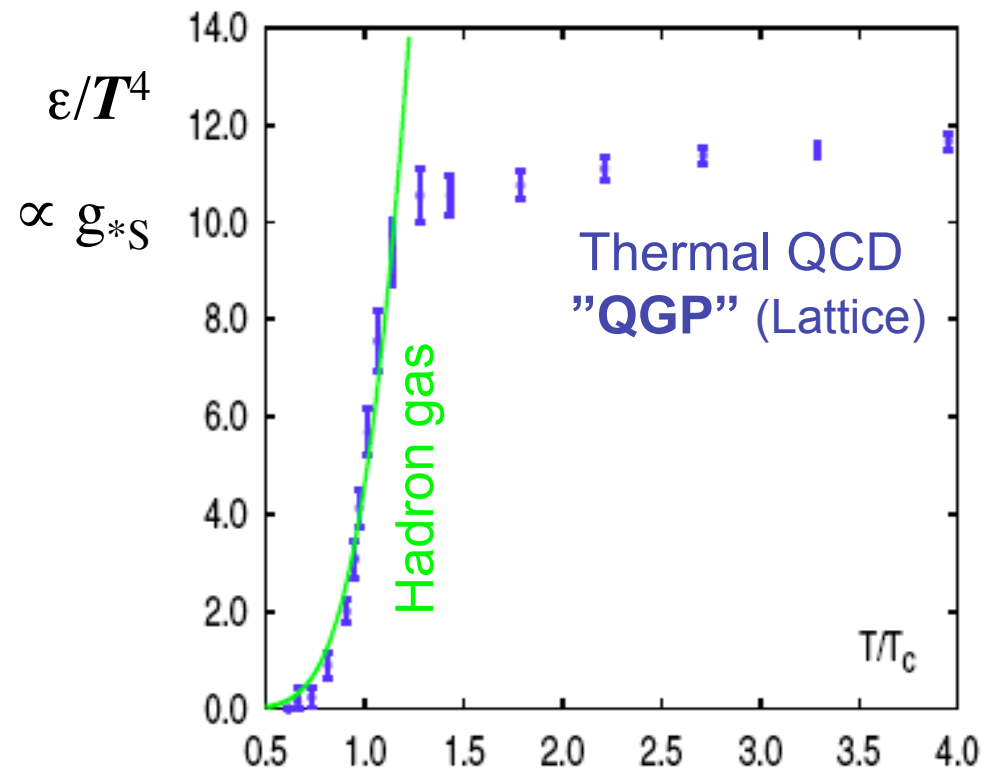
by **Quarks and  
Gluons** (simple  
and few)

“In 1972 the early universe seemed hopelessly opaque...conditions of ultrahigh temperatures...produce a theoretically intractable mess. But asymptotic freedom renders ultrahigh temperatures friendly...”

Frank Wilczek, Nobel Lecture  
(RMP 05)

D. Gross  
H.D. Politzer  
F. Wilczek  
American

QCD Asymptotic  
Freedom (1973)

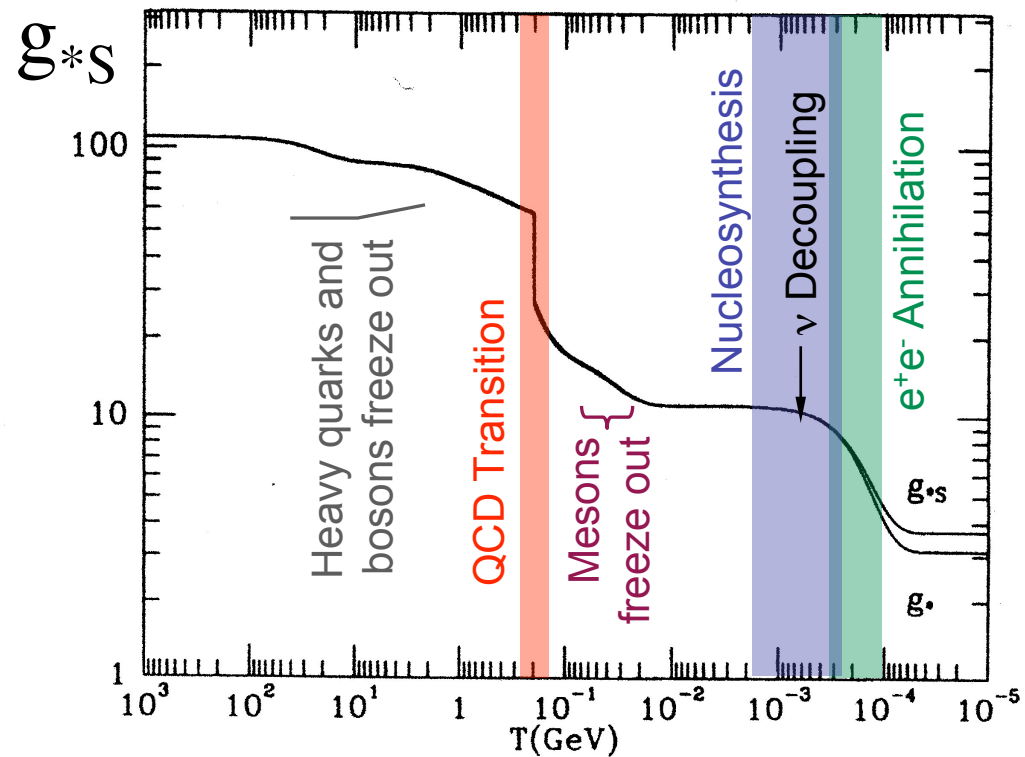


Karsch, Redlich, Tawfik,  
Eur.Phys.J. **C29**:549-556,2003

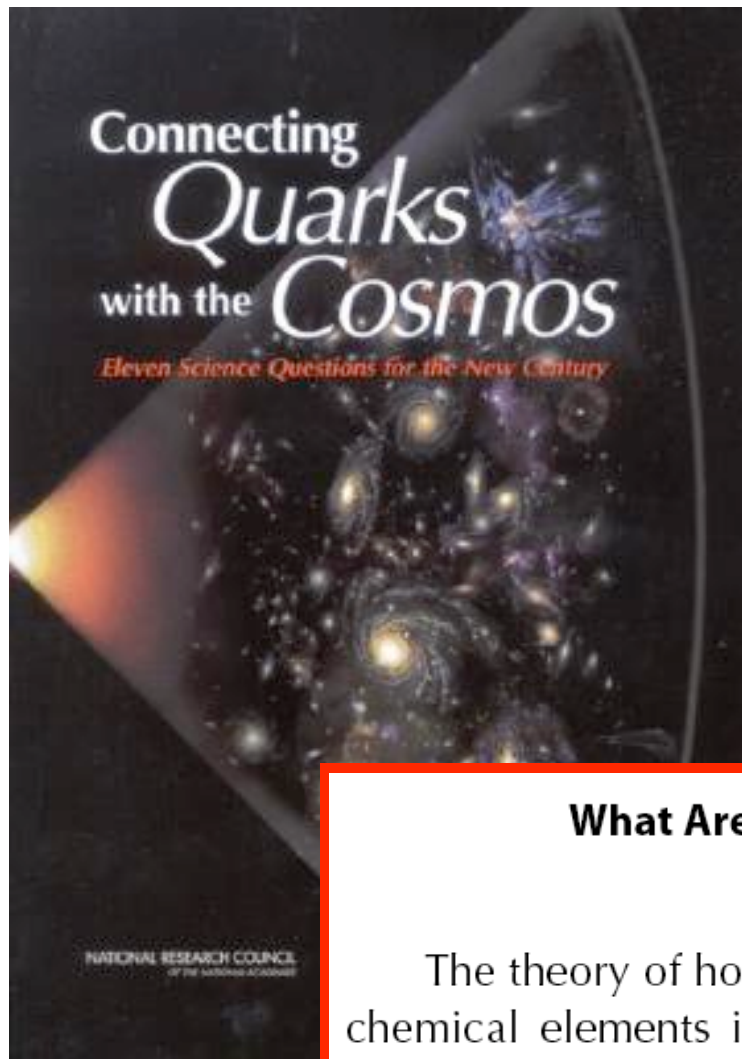
“Before [QCD] we could not go back further than 200,000 years after the Big Bang. Today...since QCD simplifies at high energy, we can extrapolate to very early times when nucleons melted...to form a quark-gluon plasma.”

David Gross, Nobel Lecture (RMP 05)

Thermal QCD --  
i.e. quarks and  
gluons -- makes  
the very early  
universe tractable;  
but where is the  
**experimental  
proof?**



Kolb & Turner, “The Early Universe”



## National Research Council Report (2003)

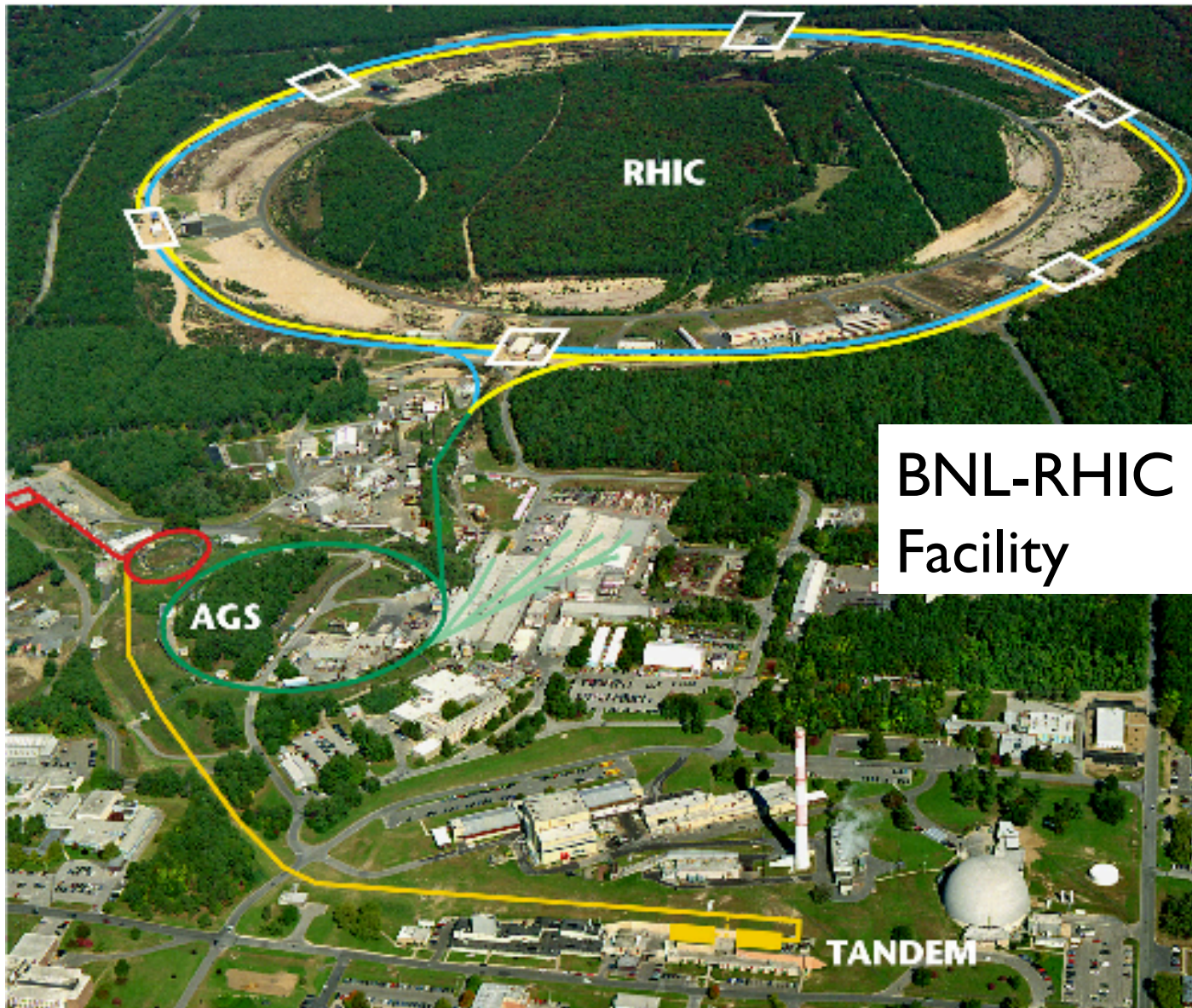
### *Eleven Science Questions for the New Century*

#### Question 8 is:

##### **What Are the New States of Matter at Exceedingly High Density and Temperature?**

The theory of how protons and neutrons form the atomic nuclei of the chemical elements is well developed. At higher densities, neutrons and protons may dissolve into an undifferentiated soup of quarks and gluons, which can be probed in heavy-ion accelerators. Densities beyond nuclear densities occur and can be probed in neutron stars, and still higher densities and temperatures existed in the early universe.



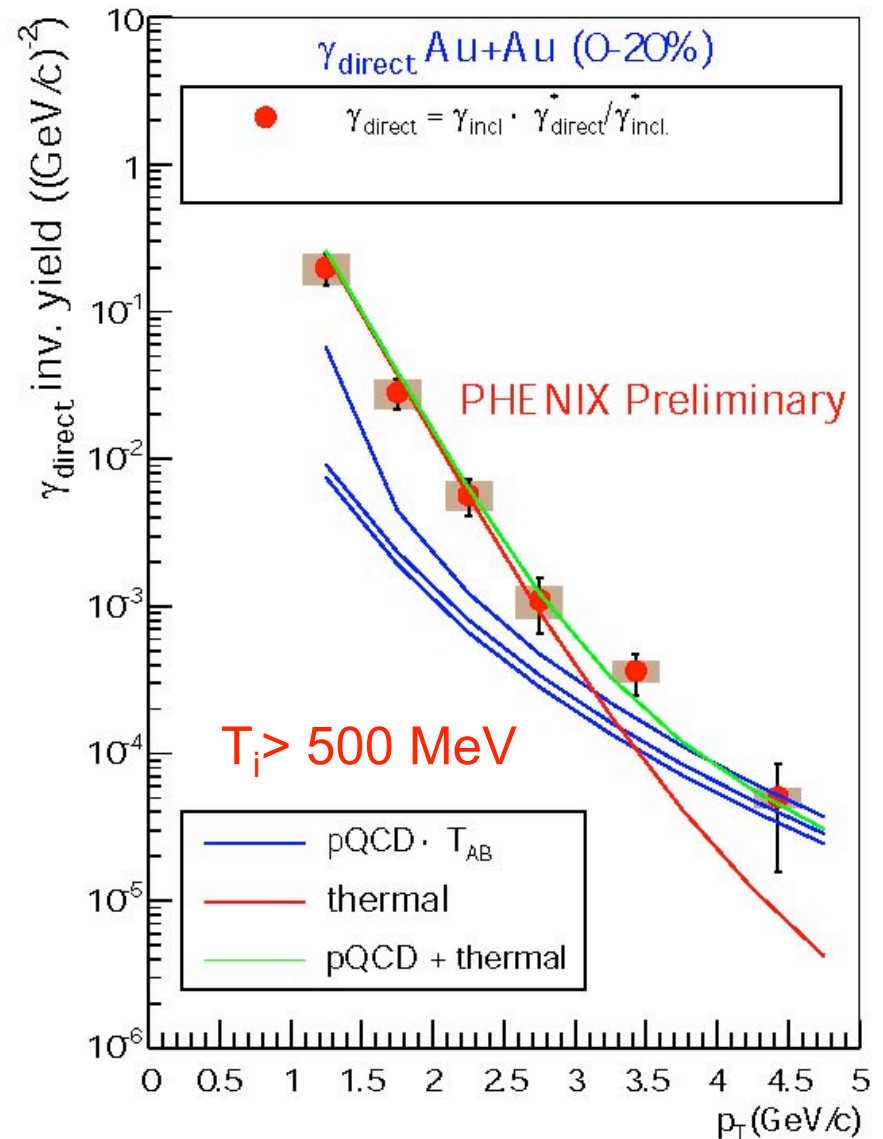
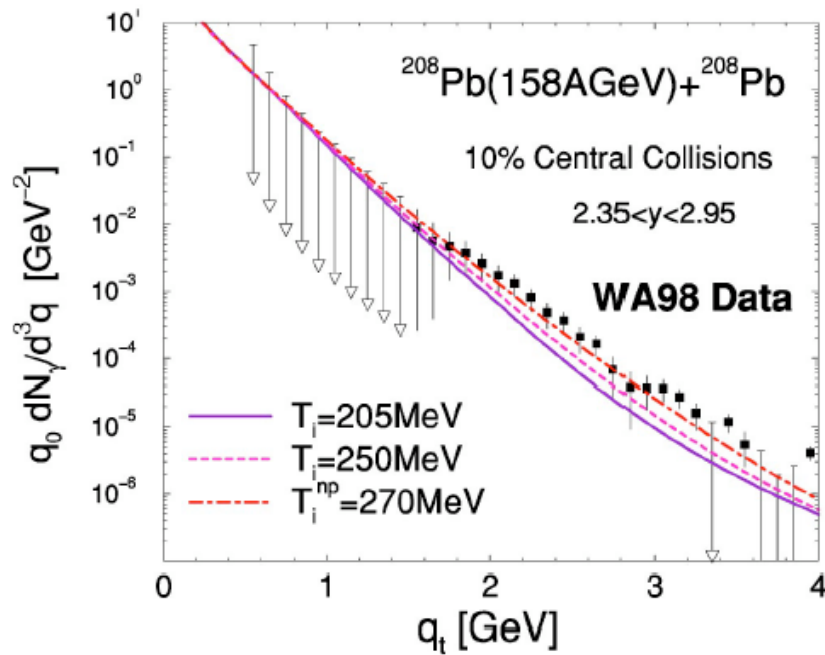


**Also:** BNL-AGS, CERN-SPS, CERN-LHC

# Temperature

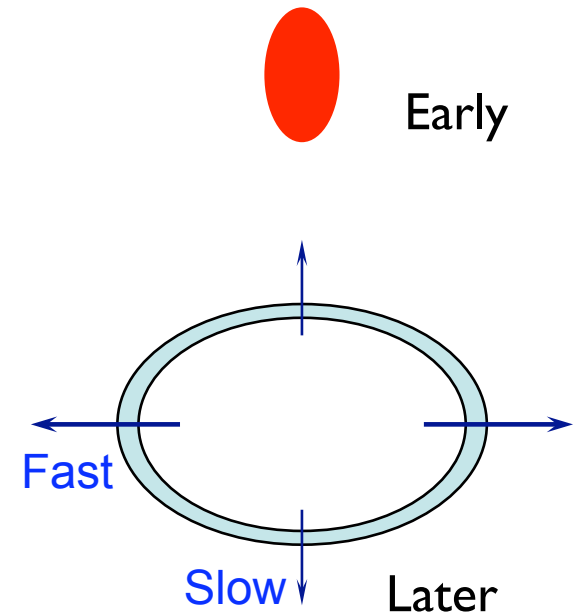
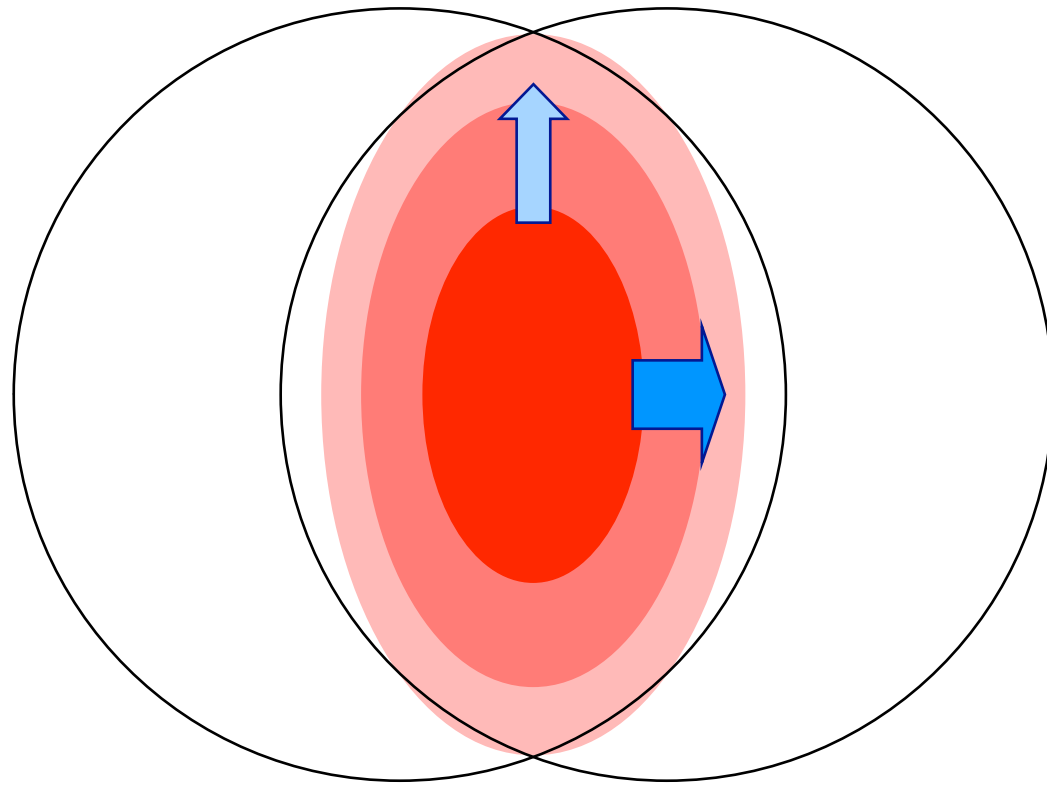
# Thermal photon radiation from quarks and gluons?

Direct photons from  
nuclear collisions *suggest*  
initial temperatures  $> T_H$

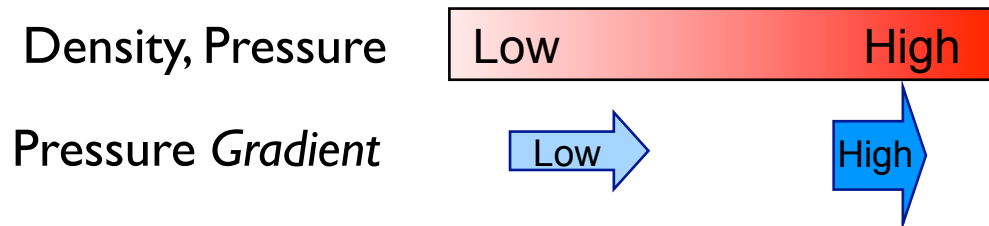


Pressure

# Initial ( $10^{-24}$ sec) Thermalized Medium



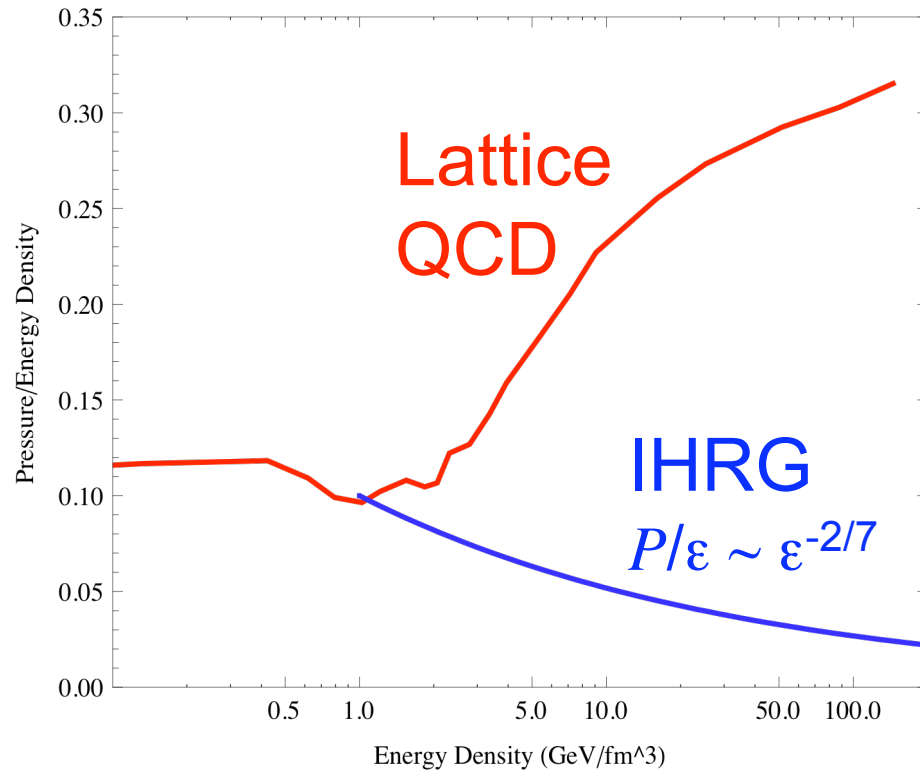
Elliptic  
momentum  
anisotropy



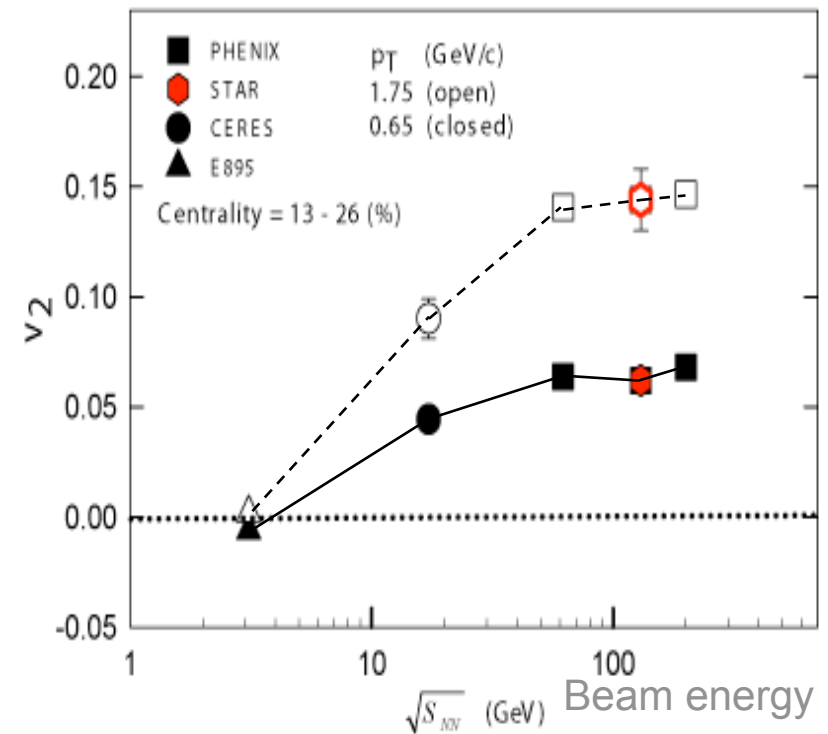
$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$



# Pressure effects *increase* with energy density



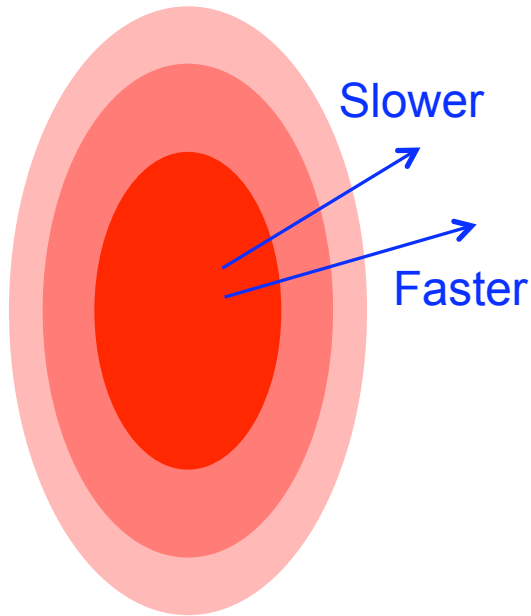
A. Bazavov et al. (HotQCD),  
arXiv:0903.4379 [hep-lat]



Phys Rev Lett 94, 232302

*Not an ideal gas*

$$\eta \text{ Shear viscosity} \approx (\text{few}) \times \underbrace{\frac{s \text{ Entropy density}}{4\pi}}_{\text{Quantum Lower Bound}}$$



$$\lambda_{\text{Mean Free Path}} \sim \lambda_{\text{de Broglie}}$$

Ideal gas  $\neq$  Ideal fluid

Long mfp  
High dissipation

Short mfp  
Low dissipation

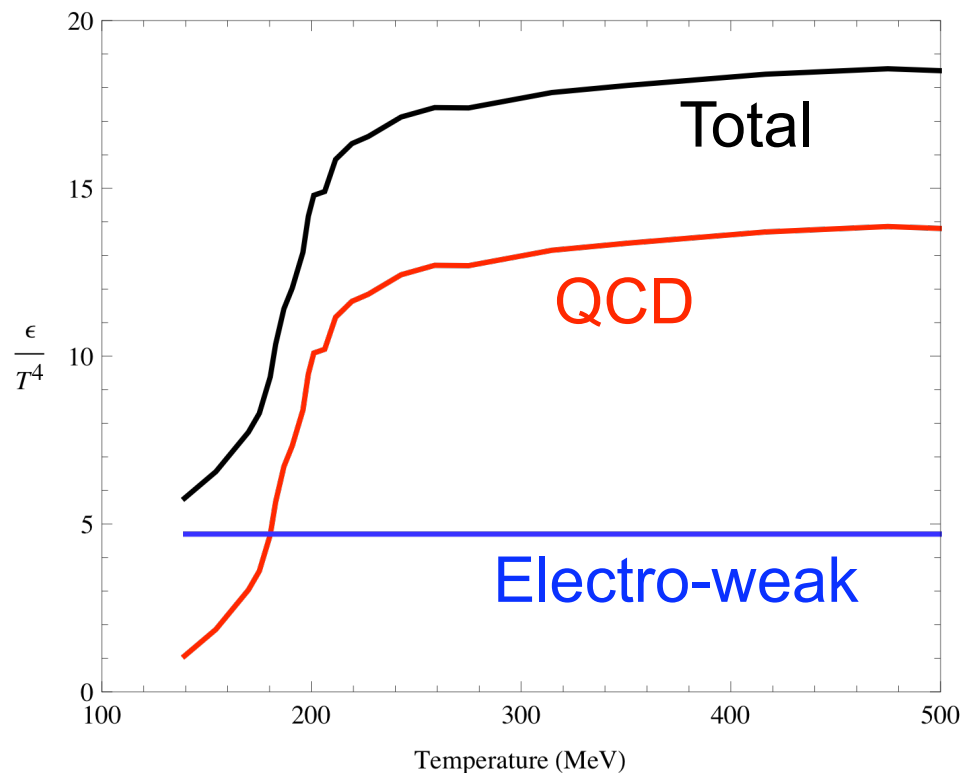
Shear Viscosity  $\nleftrightarrow$  Elliptic Flow

Low viscosity

↳ Low heat conductivity

↳ Low diffusion

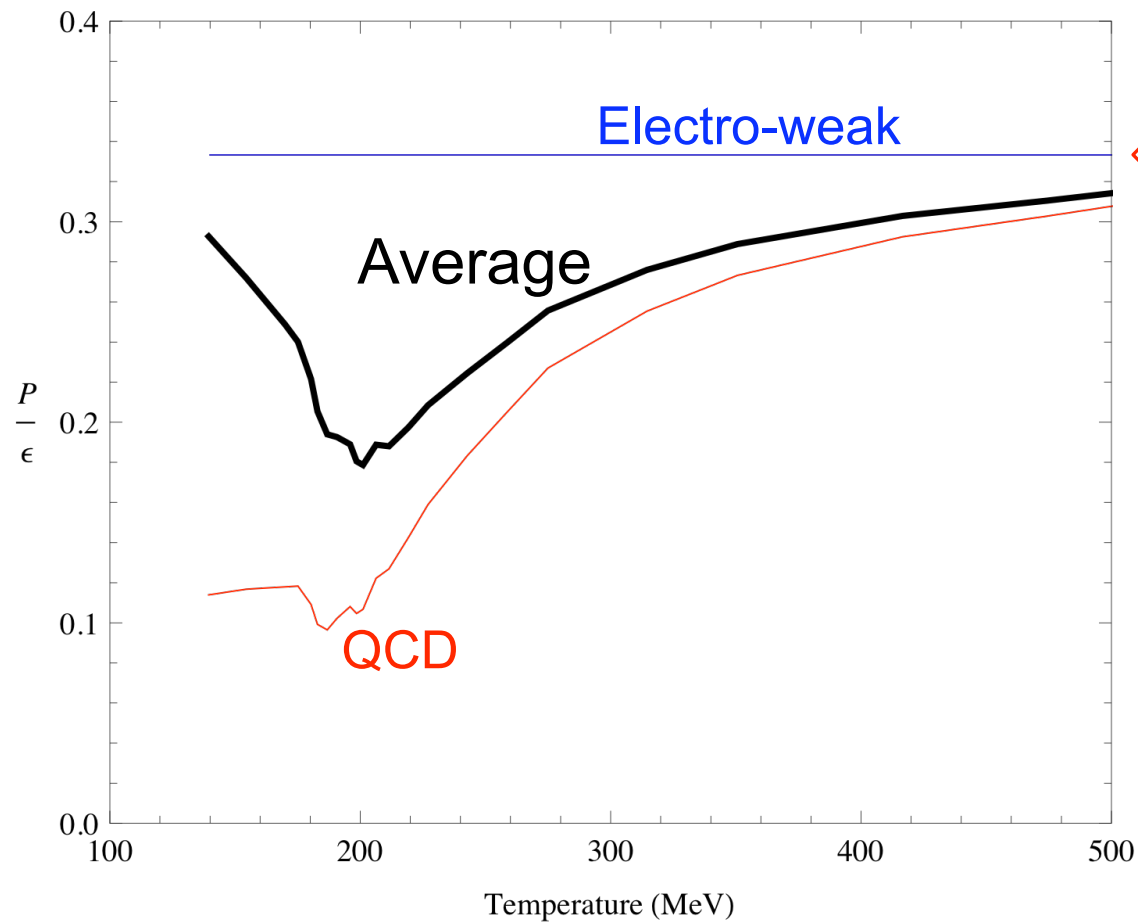
The QGP *dominates* the energy density of the early Universe for  $T > 200$  MeV



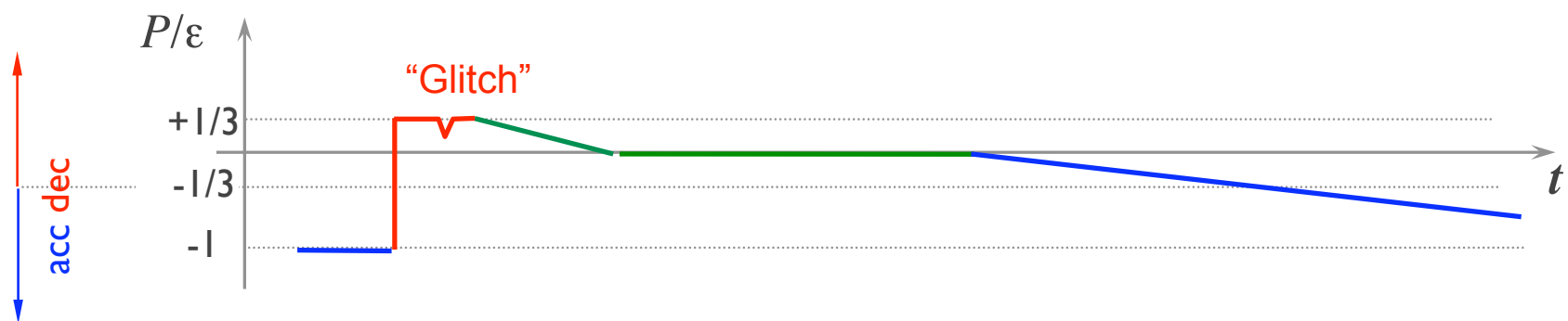
The QCD sector keeps the early universe *away* from global equilibrium:

- Low heat conduction
- Low diffusion

↳ Baryogenesis?



← Ideal  
relativistic  
gas value



The  $P/\epsilon$  of the universe dips away from radiation-dominance  $1/3$  at the QGP/Hadron transition

Conformal scalar fields coupled to

$T^\mu_\mu = \epsilon - 3P$ ; quintessence (h/t Keith Olive)

Brax, et.al., *Detecting dark energy in orbit: The cosmological chameleon*, Phys Rev D70 (2004)

Gravity waves

Maggiore, *Gravitational Wave Experiments and Early Universe Cosmology*, Phys Rep 331 (2000)

QGP horizon now expanded:

$$\text{Size today} = \text{Horizon at QGP} \frac{a(\text{now})}{a(\text{QGP})} \approx c 10^{-6} \text{s} \frac{T(\text{QGP})}{T(\text{now})} \approx c 10^6 \text{s}$$

# To take home:

- The early universe is straightforward to describe, given simplifying assumptions of isotropy, homogeneity, and thermal equilibrium.
- Strong interaction/hadron physics made it hard to understand  $T > 100 \text{ MeV} \sim 10^{12} \text{ K}$ . Ideal-gas thermal QCD makes high temperatures tractable theoretically.
- We are now delivering on a 30-year-old promise to test this experimentally. Some results confirm standard picture, but non-ideal-gas nature of QCD may have new consequences.